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A combined approach: using NAA and petrography to examine ceramic production and exchange in the American southwest

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ABSTRACT

Over the past few decades, ceramic provenance research has seen the increased use of both chemical and mineralogical analyses. However, the success of each method is dependent both on the geological environment and the behavioral processes that created the pottery under study. The combination of bulk chemical and petrographic datasets may assist in overcoming the shortcomings of each method and improve the assignment of ceramics to specific production locations. Our research uses a mixed mode approach based on dissimilarity matrices and multidimensional scaling. The resulting combined dataset helps us assess the geographic extent of production and distribution of Maverick Mountain Series and Roosevelt Red Ware pottery found in the Upper Gila and Mimbres valleys of southwestern New Mexico and southeastern Arizona. These pottery types have been connected to northern migrants arriving in these areas during the 13th century AD and subsequent regional scale social changes. This research provides a case study in the advantages of using complementary analytical techniques and combining their results to answer behavioral questions.

1. Introduction

The use of Neutron Activation Analysis (NAA) to characterize archaeological ceramics has a long history and is now a standard method for determining provenance. The resulting data, based on bulk analysis of the clay and any inclusions, can help to identify ceramic vessels likely produced using similar resources. However, relating chemical groups to geological provenance can prove challenging, even when raw clay samples are analyzed. This is especially true for sand-tempered vessels, since sand contributes to the overall chemical signature. For these ceramics, petrographic analyses are often more successful (Miksa and Heidke, 2001), but locating specific production sources can be hampered by widespread similarities in geology (Stoltman, 2001).

In many cases, petrographic analysis in conjunction with NAA has proven successful in improving the identification of production locations and tracking ceramic distribution. Several studies have shown the value of using both techniques and evaluating patterns in light of the results of each method (Bishop et al., 1982; Clark, 2006; Day et al., 1999; Eckert and Schleher, 2012; Fowles et al., 2007; Larson, 2013; Schleher and Eckert, 2012; Stoner et al., 2008; Wallis, 2011). Nevertheless, there have been studies in which the two lines of evidence have suggested different patterns of production and distribution (e.g., Blomster et al., 2005; Neff et al., 2006; Sharer et al., 2006). This may be the result of methodological differences among techniques, the geological homogeneity/heterogeneity of the study area and/or the production technology of the ceramics analyzed. While petrography may not be ideal for fine-tempered ceramics, it can be useful for assessing whether chemical group differences are the result of differential clay use within a region, or result from potters using variable amounts of similar inclusions (Buxeda i Garrigós et al., 2003). Thus, a consideration of the limitations of both techniques suggests why using only one method may lead to erroneous or ambiguous interpretations. In this article, we use an approach that incorporates information from both chemical and petrographic methods and argue that such a combined analysis can help untangle complex patterns of ceramic production and distribution.

Several previous studies have developed methods for combining chemical and petrographic datasets (Baxter et al., 2008; Cau et al., 2004; Moustaki and Papageorgiou, 2005; Rice and Saffer, 1982). These approaches merged petrographic data - coded as the presence and absence of classes of inclusions and some paste

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characteristics – with elemental concentrations. This mixed-mode approached resolved several issues relating to sample grouping and provenance determination, leading to a fuller understanding of particular cases of ceramic production and exchange. These studies were primarily carried out on Old World material; such a mixed-mode approach is rarely used in North America.

In this analysis, we apply such an approach to expand on previous studies of the production and distribution of two related ceramic traditions. Maverick Mountain Series and Roosevelt Red Ware (or Salado Polychrome) vessels have been found throughout the central and southern U.S. Southwest. Maverick Mountain Series ceramics include a related set of bi-chrome and polychrome types produced between about AD 1275 and 1450 (but most common earlier in this date range). These ceramics were unique in the southern Southwest in terms of design and technology, but are essentially analogous to ceramics produced earlier in the Kayenta region of northeastern Arizona (Neuzil and Lyons, 2006), an area that was largely depopulated in the last quarter of the 13th century. Based on such similarities, as well as a number of other lines of material evidence (Clark et al., 2013; Lyons, 2003), the production of Maverick Mountain Series pottery has been linked to the spread of immigrant populations from the Kayenta region into the southern Southwest at this time. The Roosevelt Red Ware tradition is widespread in the central and southern Southwest from ca. AD 1275–1450 (Crown, 1994; Mills and Herr, 1999). The bold and iconic designs on these elaborate polychrome vessels are thought to signify the emergence and rapid spread of new religious traditions in the Southwest (Crown, 1994). These new religious traditions and resulting hybrid identity – termed Salado by archaeologists – is related to the arrival of northern immigrants and changing patterns of interaction among locals and newcomers (Clark et al., 2013; Crown, 1994; Lyons, 2003). While available evidence indicates that Roosevelt Red Ware ceramics were initially made by immigrant potters (Clark and Lyons, 2012; Crown, 1994; Lyons, 2003; Lyons and Clark, 2012; Lyons and Lindsay, 2006), by AD 1325 this tradition dominated the ceramic assemblages of most communities across a large swath of the southern Southwest (Clark et al., 2013; Crown, 1994; Lyons, 2003; Mills et al., 2013). The production and circulation of Roosevelt Red Ware ceramics and Salado identity flourished as culturally diverse groups of people, including immigrants from the northern southwest and the descendants of earlier populations in the southern Southwest, were united by inclusive religious beliefs and practices (Fig. 1).

Past research on these ceramic traditions suggests that they were made in many of the places that they were found (Crown, 1994; Crown and Bishop, 1991; Danson and Wallace, 1956; Duff, 2002; Hill, 1998; Lightfoot and Jewett, 1984; Lyons, 2003, 2012; Martin and Rinaldo, 1960; Mills et al., 1999; Neuzil, 2008; Simon et al., 1998; Stinson, 1996; Zedeño, 1994), but this question has not been addressed for the Upper Gila and Mimbres regions of southwestern New Mexico and southeastern Arizona. In addition to providing a more spatially complete picture of the spread of Salado-associated pottery and identity, we also wanted to determine if Maverick Mountain Series pottery and Roosevelt Red Ware were both produced in the study area and whether production locations remained stable from the late 13th through 15th centuries. Identifying provenance was necessary to assess continuity between the two wares, which would support a connection between initial Kayenta migration and later Salado florescence.

The decision to use both NAA and petrography and combine the resulting data was made based on our knowledge of regional geology, which also framed our research questions. We needed to locate production sources for fine-tempered ceramics in a region with some geological homogeneity. The presence of different outcrops with similar rock types in the greater Upper Gila region led us to expect that site-based differences would be difficult to discern. However, we felt that geological differences between the Upper Gila and Mimbres valleys and the sampled locations in southeastern Arizona were sufficient to allow us to discriminate among products from different areas using NAA. We expected the

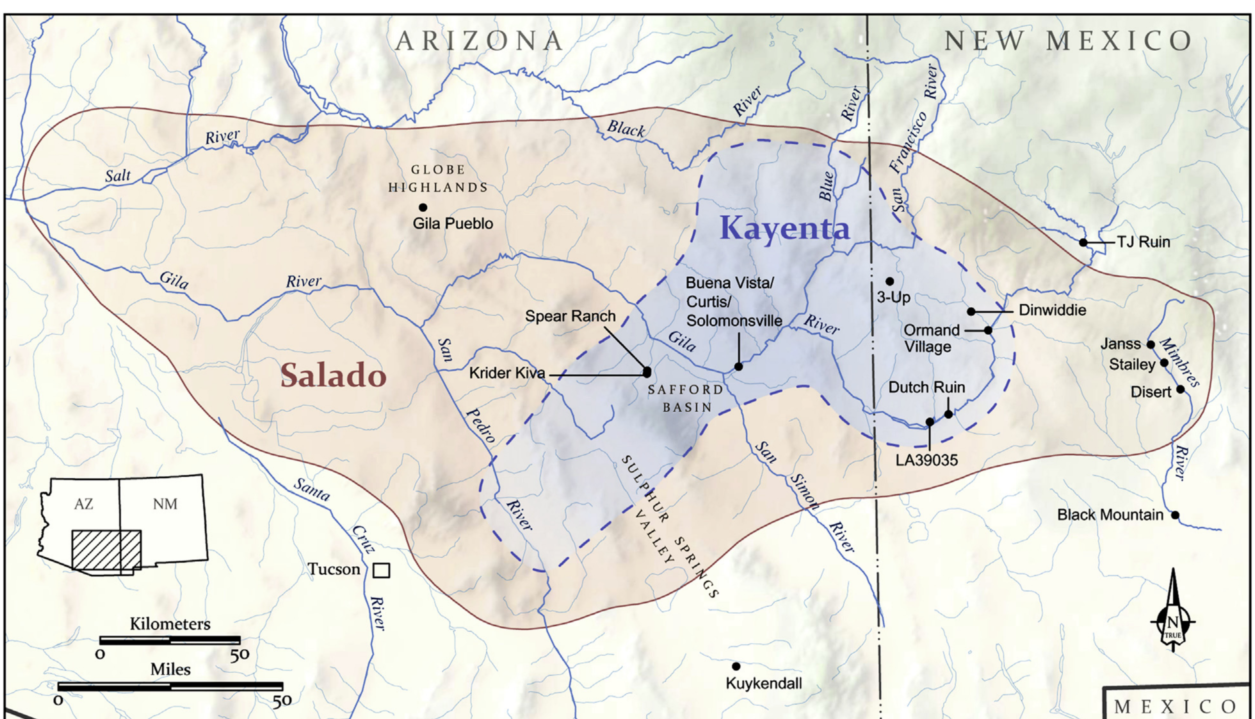

Fig. 1. Locations mentioned in the text, including areas of archaeologically documented Kayenta migration (darker shading) and the extent of Salado polychrome distribution (larger, lighter shaded area).

petrographic data to assist in determining whether chemical groups separated due to overall temper abundance or due to the use of different temper materials. We combined NAA and petrographic datasets in a mixed-mode analysis following Baxter et al. (2008).

1.1. Geology

Southeastern Arizona and southwestern New Mexico are both characterized by basin and range topography. Geologically, southwestern New Mexico is dominated by volcanic outcrops of various types and ages (Elston, 1965). Older formations, typically postdating the Cretaceous period, are mostly rhyolitic with less common dikes of andesite or basaltic andesite. Thick rhyolite and tuff deposits characterize the Tertiary period, while more recent outcrops are typically basaltic. Weathering has resulted in the formation of Oligocene Gila Group (OGG) deposits, comprised mostly of conglomerate, sandstone, and basaltic andesite, which cover a majority of this area and contribute greatly to the Quaternary surfaces upon which most sites are found (Fig. 2). Precambrian granites and metamorphic rocks are rare, although some are found in the southern part of the Mimbres River Valley and in the Burro Mountains to the east of Dutch Ruin (see Fig. 1). Cretaceous sedimentary rocks, mostly sandstones, limestones, and shales, are also uncommon.

Similar to southwestern New Mexico, southeastern Arizona also has prevalent volcanic outcrops that vary in their composition between rhyolite and basalt, but there are outcrops of dacite and a few of diabase. Additionally, there are notable areas of granite, particularly in the Safford Basin. Metamorphic rocks are present as well in the Safford area and Globe Highlands.

1.2. Ceramic types

Throughout their distribution in central and southeastern Arizona and southwestern New Mexico, Maverick Mountain Series

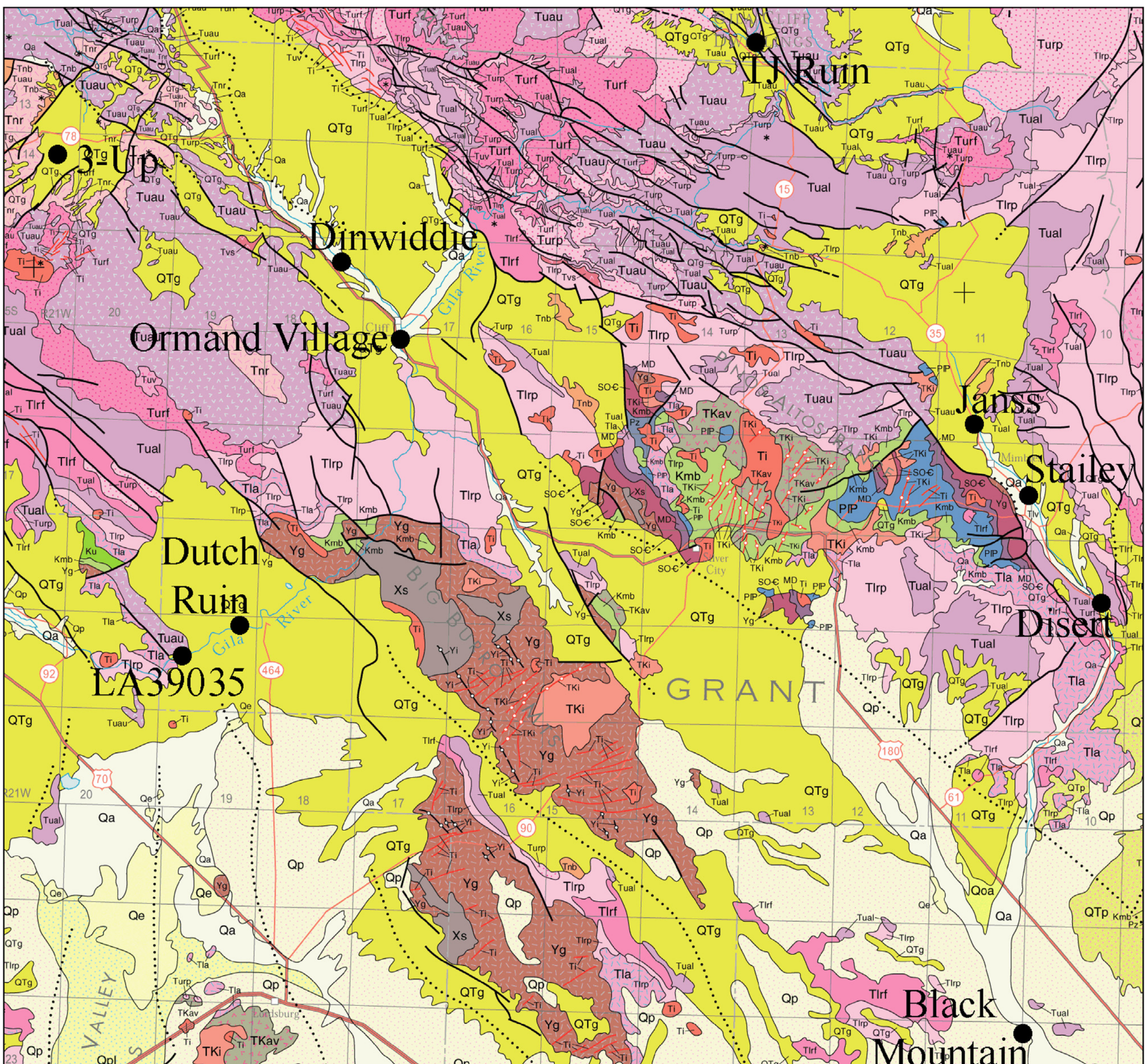

Fig. 2. Geological map of southwestern New Mexico showing sampled sites in this area. Based on Scholle (2003).

ceramics (MMS) are essentially locally made copies of northern Kayenta and Tusayan pottery (Breternitz et al., 1957; Neuzil and Lyons, 2006). MMS vessels have brown pastes and usually contain fine-sand temper. Both interior and exterior surfaces of most varieties are slipped red and designs are rendered in black mineral paint or a combination of black, red and white paint (Fig. 3a).

Like MMS pottery, Roosevelt Red Ware (RRW) vessels are most often manufactured using coil-and-scrape technology and have brown pastes and, typically, fine-sand temper (Neuzil and Lyons, 2006). Vessel surfaces are red and/or white-slipped and the interior surfaces of some varieties are smudged black (Fig. 3b). Technological and iconographic similarities between RRW and Kayenta pottery suggest that the former was strongly influenced by immigrant ceramic traditions (Crown, 1994; Lyons, 2003, 2012). The presence of Belford Plain perforated plates (believed to be pottery making tools used by Kayenta potters) at many 14th through 15th century sites with relatively large quantities of RRW is further evidence of this connection (Lyons and Lindsay, 2006).

2. Methods

2.1. Neutron activation analysis

This study began with NAA of 470 samples of MMS, RRW, plain brown and red-slipped utility ware, and Belford Plain perforated plates from 16 archaeological sites in 5 different regions (see Fig. 1; Table 1). We included the utility ware and plate samples based on the assumption that they should represent local production using readily available raw materials (Graves, 1991; Sahlins, 1972; Stark, 1992). Thus they should provide a "local" petrographic signature for comparison with possibly imported decorated types. Petrographic analysis, discussed below, supported this assumption as utility ware samples typically contained sand temper consistent with local geology.

NAA data were acquired at the University of Missouri Research Reactor (MURR) utilizing their standard procedures (Glascock, 1992; Neff and Glowacki, 2002:4). For many samples, no data were acquired for the element Ni, and we excluded this element from our analysis. The elements As and Na were also excluded, the former due to firing issues and the latter to post-depositional mobility (Cogswell et al., 1996). The raw data were transformed to base 10 logarithms for statistical analysis to ensure roughly equivalent variances for all elements (Bishop and Neff, 1989:63, 72; Baxter, 2003:75). We used four statistical tests to identify robust sample grouping patterns and to highlight problematic samples (outliers) and less coherent groups of samples. The tests included principal components analysis (PCA), followed by hierarchical cluster analysis, stepwise discriminant analysis employing a Mahalanobis distance measurement, and finally K-means cluster analysis on standardized PCA scores (Shennan, 1997; Baxter, 2003). We also used an iterative process of Mahalanobis distance posterior classification available as part of MURR's GAUSS program to assess sample group assignment probabilities.

Table 1
Samples for NAA; parentheses show samples for petrographic analysis.

Site	Maverick Mountain Series	Salado polychrome	Utility wares	Belford plain perforated plates	Total
Upper Gila					
3-Up	21 (1)	33 (1)	24	1 (1)	79
TJ Ruin	0	13 (1)	10 (1)	0	23
Ormand Village	21 (1)	31 (1)	15 (1)	0	67
Dutch Ruin	3	20 (2)	11 (1)	0	34
LA 39035	1	2	4 (1)	0	7
Dinwiddie	5 (1)	20 (1)	5 (1)	0	30
Safford Area					
Buena Vista/Curtis/ Solomonsville	13	15 (1)	6 (1)	0	34
Spear Ranch/ Krider Kiva	15	30 (1)	6	4 (2)	55
Mimbres Valley					
Janss	0	15	10 (2)	0	25
Stailey	0	12 (2)	4	0	16
Disert	0	20 (2)	10 (1)	0	30
Black Mountain	6 (1)	7	1	0	14
Sulphur Springs Valley					
Kuykendall	5	15 (1)	6 (1)	0	26
Globe Highlands					
Gila Pueblo	0	29 (1)	0	1 (1)	30
Total	90	233	112	5	470

2.2. Petrographic analysis

Petrographic samples were chosen from each defined chemical group, with several additional considerations for sample selection meant to ensure that petrographic analysis would successfully clarify geological and behavioral processes reflected in the NAA groups. First, areas with notable geological differences were sampled less intensively than those, such as the Upper Gila

Fig. 3. a) Maverick Mountain Series jar, and b) Roosevelt Red Ware bowl. Photos by Mathew A. Devitt courtesy of Eastern Arizona College.

drainage, where a single geological outcrop (the OGG) dominated. Site proximity was also a consideration, since a few sites, like Krider Kiva and Spear Ranch, are adjacent and likely had access to very similar raw materials. We selected 32 samples for petrographic analysis, including 10 utility ware sherds, 4 MMS sherds, 14 RRW sherds, and 4 sherds from perforated plates (see Table 1; Supplemental data provides more detail on sample selection).

The petrographic analysis was qualitative in that it focused on the relative proportions of different minerals and rock fragments comprising the temper as assessed visually rather than with point-count data (Whitbread, 1989).[1] Given the broadly comparable geology of the study area, we felt that knowing relative frequency differences in inclusions would allow us to distinguish sand tempers in sherds from different areas. The petrographic data included the grain frequencies for 38 mineral and rock fragment categories (see Supplemental data for more information on methodology). Numerical values were zero (absent), 1 (1–5 grains), 2 (c. 10% of inclusions), 3 (10–25%), and 4 (25–50%). For the combined data analysis, we chose to use these categories rather than to binarize the data so as to allow for the consideration of as much of the variability in the dataset as possible. We also recorded matrix (fired paste) color in plane and cross polarized light, optical activity of the matrix (to assess general firing temperature), percentage of inclusions, sorting, and size and shape range of inclusions. Additionally, differences in the appearance of the clay between samples were noted, although clay minerals themselves cannot be identified petrographically.

2.3. Combined data analysis

In order to combine the NAA and petrographic datasets, we followed procedures developed by Baxter et al. (2008). First, we conducted both correlation and correspondence analyses (CA) on the petrographic and NAA data to identify variables meriting removal and potential outliers in both data sets. The former test identified nine petrographic categories that could be removed based on their general absence in the samples, resulting in 29 categories for further analysis (see Supplemental data Table 1). CA plots were particularly useful in highlighting outliers in both the petrographic and NAA data, as explained in detail in the Supplemental materials. Next, following Baxter et al. (2008), we implemented a method of mixed-mode analysis to consider both the petrographic and NAA data simultaneously (see supplement for R code). In short, the procedure involves the creation of dissimilarity and distance matrices among all samples for each type of data and the mathematical combination of these two matrices. Specifically, we used Gower's coefficient (Gower, 1971) to create a matrix of standardized petrographic dissimilarities among all samples based on the numerical values described above; the resulting values were scaled to range between 0 and 1. For the NAA data, we calculated a matrix of Euclidean distances among those same samples based on the log-transformed values (again scaled to range between 0 and 1). Following method 2 presented by Baxter et al. (2008), the two matrices were combined using the formula $D_M = (M^*D_c) + (1-\mu)^*D_m$ where D_c is the matrix of distances based on NAA data and D_m is the matrix of dissimilarities based on petrographic data. The value μ is a parameter which allows us to determine the relative weight of NAA and petrographic data in the resultant matrix of dissimilarities. A value of 0.5 gives equal weighting to both the petrographic and compositional data, a value of $M = 1$ would rely only on chemical data, and a value of $M = 0$ would only consider mineralogical data. As described further below, we tested a range of values of μ. The resulting combined dissimilarity matrices for multiple values of μ were then subjected to multidimensional scaling (MDS) producing a two-dimensional representation of the relationships among individual samples. These MDS analyses were initially run for all 32 samples and also after the removal of far outliers in the combined MDS, which were the same as those highlighted in individual data sets using CA as described above.

In order to test the effect of the mixed-mode analysis on the resulting MDS analyses for various values of μ, we used Procrustes analyses to directly compare MDS configurations to those produced considering either the NAA or petrographic data alone (see Supplemental data for additional description of this method). Fig. 4 displays the results of this procedure, showing the sum of squared difference between the mixed-mode MDS configuration and the MDS configurations based only on chemical and only on petrographic data. A value of 0 for this sum of squared difference measure indicates that two MDS configurations are identical and values greater than 0 indicate increasing difference between the configurations considered (in other words, lower values indicate greater similarity between two MDS configurations). The two lines in this plot illustrate changes in the association of each mixed-mode MDS analysis (for varying values of μ) with MDS of chemical or petrographic data alone. As this plot illustrates, values that diverge greatly from $\mu = 0.5$ show strong similarities to results generated by either NAA or mineralogical data only and only values in a small range between about $\mu = 0.4$ and $\mu = 0.6$ show similar sum of squared difference values to both the chemical and petrographic MDS configurations. This result is nearly identical to that observed by Baxter et al. (2008). For this reason, in the discussion below, we present results for the intermediate value of $\mu = 0.5$, as well as two more extreme values in either direction ($\mu = 0.25$ and $\mu = 0.75$) to illustrate changes in MDS as the contributions of each data set are altered. In practice, we tested values between 0 and 1 in intervals of 0.05, but the results presented here are representative of patterns documented across a broader range of values.

3. Results

3.1. NAA data

Statistical analysis of the NAA dataset identified 18 groups,[2] along with a number of unassigned samples (Table 2). Utility ware samples dominate several groups, suggesting they reflect local production of these vessels (Fig. 5a). This applies to Group 2 with sherds from TJ Ruin, Group 4 consisting of samples from Dutch Ruin, Group 5 comprising sherds from LA39035, Group 13 with samples from the proximate sites of Janss and Stailey, Group 15 containing sherds from Disert, and Group 20 having only three utility ware samples from Kuykendall. A number of other groups contain both utility and decorated sherds mostly from one site. These groups likely represent local decorated and utility ware production using similar raw materials. For example, Group 1 contains mostly utility and decorated sherds from 3-Up and Group 6 has both decorated and utility ware samples from Dinwiddie. Nearly all of the utility and decorated sherds from Krider Kiva and Spear Ranch, located next to each other, are in Group 11. This

[1] We did not perform point counting as the scope of our study necessitated exploring the efficacy of a qualitative approach that would give an initial impression into geological differences.

[2] Final group numbers are not consecutive because some groups were eventually combined or eliminated. Although in two-dimensions (see Fig. 5a and b) the groups appear to overlap, the Mahalanobis probabilities for each sample's assignment to a particular group are generally strong.

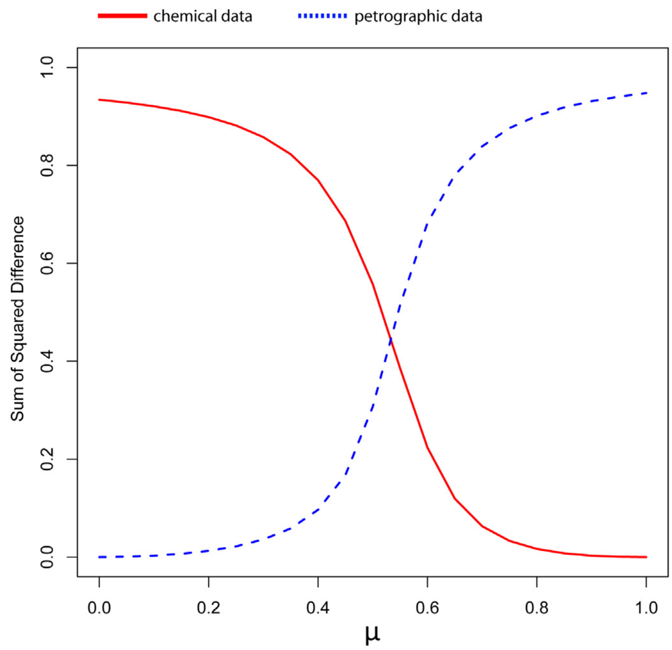

Fig. 4. Sum of squared difference for comparisons of MDS plots using different values of μ for NAA data (Euclidean distances) and petrographic data (Gower's coefficient).

pattern indicates that these villages probably made MMS and RRW pottery in addition to utility ware vessels.

While some groups are fairly easy to interpret, six groups include mostly decorated samples from a number of different sites (Fig. 5b). Group 3 contains utility and decorated ware sampled from eight different sites in the Upper Gila, Mimbres, and Sulphur Springs valleys. However, many samples derive from Ormand Village; indeed almost all the utility ware sherds are from this site, suggesting Group 3 may signify MMS and RRW production at Ormand. Similarly, Group 10 has mostly decorated samples from a number of sites, but samples from Buena Vista/Curtis/Solomonsville (BVC) dominate, possibly indicating this is the source for all of the MMS and RRW samples in the group. The samples in Group 19 are decorated sherds predominantly from sites in the Upper Gila and Mimbres valleys, as well as Kuykendall in the Sulphur Springs Valley. As no individual site dominates the group, we cannot attribute it to a particular production location. The same situation occurs with groups 21, 22, and 23, which contain decorated vessels from many sites in different valleys. As discussed below, we attribute these groups to production using geologically similar raw materials by villages located along the Upper Gila and its tributaries. Finally, groups 25, 26, and 27 include decorated ware samples almost entirely from Gila Pueblo in the Globe Highlands. The distance of this site from the other areas likely explains why the majority of the samples are easily chemically discernible. Their separation into distinct groups suggests that while some vessels were probably made at Gila Pueblo, others likely came from other locations, such as villages in the Tonto Basin and Phoenix area.

3.2. *Petrographic data*

The petrographic analysis examined samples from each chemical group (see Supplement data Table 2). Most utility ware samples have sand temper that matches the local geology. For example, the TJ Ruin sample (in chemical Group 2) contains local rhyolitic tuff. Likewise, granite in the Dutch Ruin sherd (Group 4) and the LA39035 sample (Group 5) is likely derived from a Middle Proterozoic pluton near these sites (Fig. 6a). Analysis of utility ware from the Mimbres Valley sites indicates that the two samples from Janss (Group 13) were likely locally produced using volcanic sand temper. The sample from Disert (Group 15) has similar temper and clay suggestive of local manufacture. Finally, a utility ware sherd from Kuykendall (Group 20) has sand temper with granite and rhyolite rock fragments that undoubtedly occur near the site.

For some sites, utility and decorated ware samples appear petrographically similar, suggesting local production of MMS and

Table 2
Chemical groups identified in the NAA data, separated by site and utility ware versus decorated ware.

Site	Ware	1	2	3	4	5	6	10	11	13	15	20	19	21	22	23	25	26	27	Un-assign	Total
3-Up	Dec	15						1					2	22	6	1				7	54
	Utility	23																		2	25
TJ Ruin	Dec			1			2	1						4	2					3	13
	Utility		7																	3	10
Ormand	Dec	2		20			1	1		1			1	9	6	2				9	52
	Utility			9																6	15
Dutch Ruin	Dec			2					1				1	6	5	5				3	23
	Utility				8															3	11
LA 39035	Dec			1										1		1					3
	Utility					3														1	4
Dinwiddie	Dec			6			5	2		1				6	3	1				2	26
	Utility						3													1	4
BVC	Dec							13					2	7	1	1				4	28
	Utility							1												5	6
Spear/Krider	Dec								43								1			1	45
	Utility								10												10
Janss/Stailey	Dec			1				3					2	3	14			1		3	27
	Utility									12	1									1	14
Disert	Dec			4						1	1		1	3	4	2				4	20
	Utility										9									1	10
Kuy-kendall	Dec			4				1	2				4		2					7	20
	Utility											3								3	6
Black Mtn	Dec							1		1			2	6		1				2	13
	Utility																			1	1
Gila Pueblo	Dec							2									5	15	5	2	29
	Utility																			1	1
TOTAL		40	7	48	8	3	11	26	56	16	11	3	15	67	43	14	6	16	5	75	470

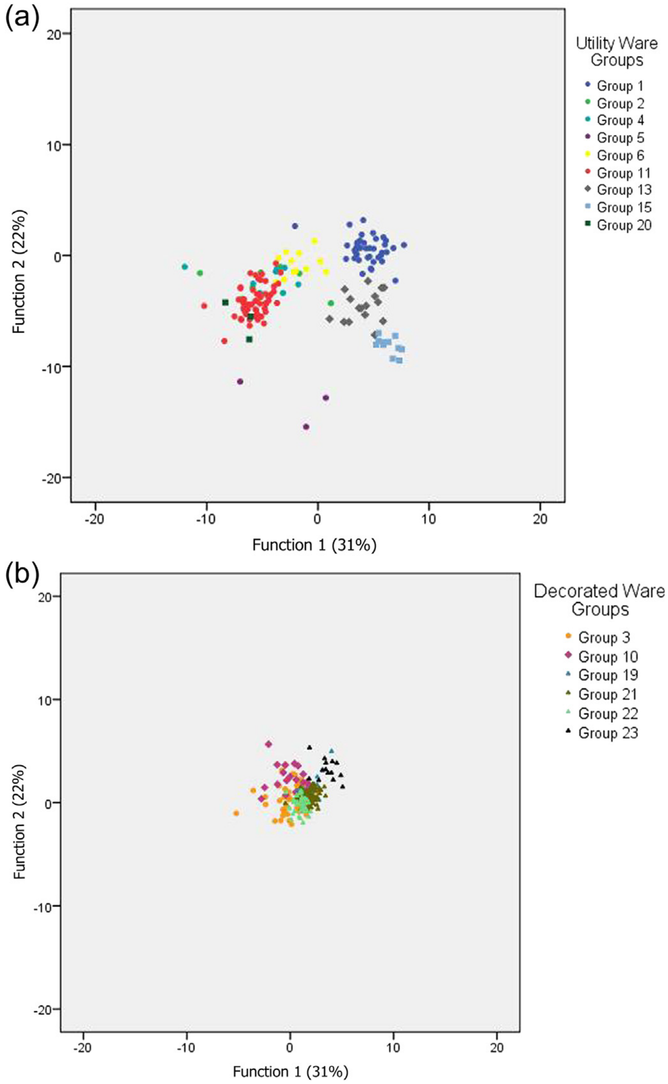

Fig. 5. Results of discriminant analysis, a) utility wares; b) decorated wares. Geological differences in utility ware probably explain their separation, while decorated ware was made with similar volcanic sand and clay.

RRW. For example, the utility ware and RRW samples from Dinwiddie (Group 6) are petrographically similar, suggesting potters from this village made both wares, although they used different clay for the utility ware. The samples from Krider Kiva/Spear Ranch (Group 11) include two perforated plates and a RRW sherd, all of which contain sand temper with common granite and a few metamorphic rock fragments. A perforated plate from 3-Up (Group 1) contains volcanic sand that matches the local geology. Thus, chemically similar vessels in this group, including decorated types, were probably produced at 3-Up. The RRW sherd from Ormand Village (Group 3) has volcanic sand that resembles sand in an unfired utility ware sample from this site, although once again, the utility and decorated ware clays are different. Interestingly, the RRW sample from Ormand is analogous to a RRW from Kuykendall and a MMS from Dinwiddie, possibly suggesting Dinwiddie and Kuykendall residents acquired decorated vessels made at Ormand Village. In contrast, petrographic analysis of a utility ware sample from BVC contained temper that could be locally derived, but it was not similar to the RRW from the site (Group 10, which contained many decorated sherds from BVC). This may indicate a difference in raw materials for MMS and RRW made at BVC.

Petrographic analysis of MMS and RRW samples from chemical groups dominated by decorated ware reveals that most contain volcanic sand temper that likely originates from OGG deposits along the Upper Gila River. This applies to two RRW samples from 3-Up and one from Dutch Ruin (both in Group 21), as well as a RRW from Dutch Ruin in Group 23 (Fig. 6b). Although we did not petrographically analyze any samples from Group 19, it is chemically similar to Group 23, and thus likely also indicates Upper Gila decorated ware production. The two RRW samples from Stailey and one from TJ Ruin in Group 22 also have sand temper with common volcanic rock fragments similar to samples made along the Upper Gila, suggesting the vessels are imports to these sites. It is probable that we have not included samples from every pottery-producing site in the study area, and this might explain why a provenance for these chemical groups is unclear.

Petrographic analysis of a RRW sample from Gila Pueblo (Group 26) suggests it was not locally produced, since its sand temper is dissimilar to a sand sample collected near the site (Montage-Judd et al., 2003). Further, it is petrographically dissimilar to a perforated plate from Gila Pueblo.[3] Based on regional geology, the RRW may have been produced somewhere to the north of the site. Other unassigned samples, a RRW from Ormand Village and a RRW from Disert, contain sand temper likely derived from the OGG, which suggests production somewhere along the Upper Gila. These vessels are petrographically similar to a MSS from Black Mountain, but it was not possible to determine if the sand was local or not.

3.3. Results from combined NAA and petrographic data

Combining our chemical and petrographic datasets allowed us to clarify patterns of production and distribution suggested by our individual analyses. Following Baxter et al. (2008), we first examined the combined dissimilarity matrices including all samples, as discussed above (Fig. 7; see Supplemental data). A small number of outliers that are clearly separated from the main group were then removed. These outliers are petrographically and chemically distinct utility ware sherds locally produced at several sites. Next, we produced dissimilarity matrices for the remaining 27 samples and examined MDS plots using values of μ set to 0.25 (A), 0.5 (B), and 0.75 (C) (Fig. 8). When a value of 0.25 is used for μ, the resulting plot is weighted primarily towards the petrographic data. The plot shows a loose central cluster that probably reflects use of OGG sands as temper. Notably, the Mimbres Valley samples appear mineralogically similar to samples from Upper Gila sites, and Mimbres Valley utility and decorated ware are not all that distinctive from one another. The cluster at the far right contains samples with less altered plagioclase and felsic volcanic rock fragments. The two samples from Gila Pueblo (far lower left on the plot) are notably dissimilar from most of the others.

Using a μ value of 0.5 (equal weight to chemical and petrographic data), samples are dispersed on the plot but appear to cluster loosely into one group from Ormand Village, Dinwiddie, and Krider Kiva/Spear Ranch, and a second loose cluster of samples from chemical groups dominated by decorated ware, particularly Groups 21 and 22. In addition, at a μ value of 0.5, the Mimbres Valley decorated and utility ware samples begin to separate, which becomes even clearer in the 0.75 plot (chemical data emphasis). In this plot, decorated ware samples from Kuykendall and Gila Pueblo also stand out as chemically distinctive from the Upper Gila, Mimbres, and Safford Basin samples. As discussed further below, these specific patterns (the distinctiveness of the Globe Highlands

[3] This was not assigned to a chemical group but we think it is local because the inclusions are similar to the geology around the site.

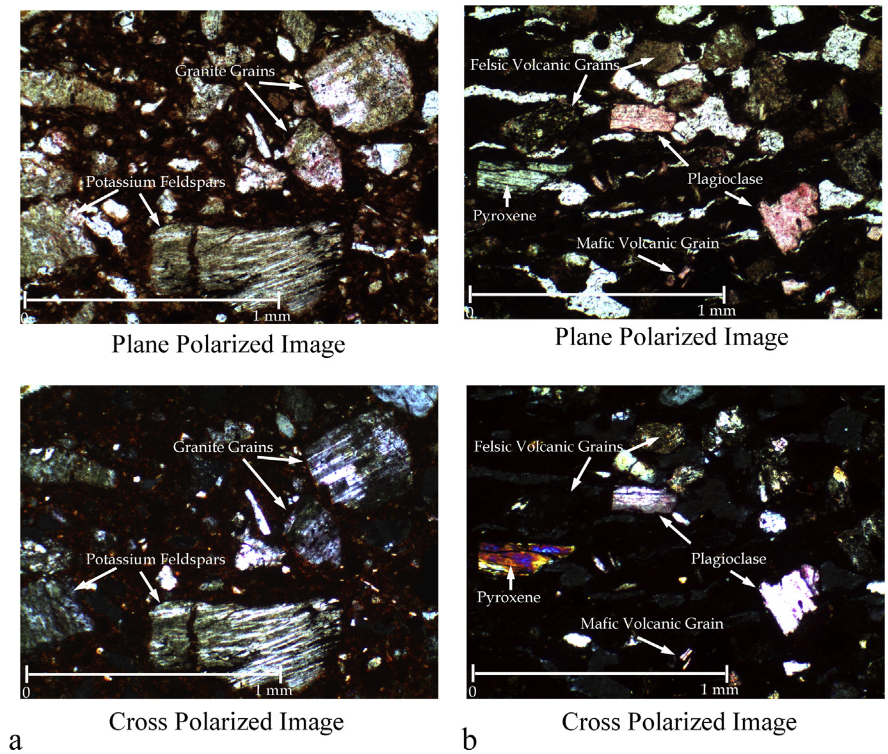

Fig. 6. Thin section images, a) utility ware with granite sand temper; b) RRW with volcanic sand temper. Both from Dutch Ruin.

and Sulphur Spring Valley samples and the lack of strong associations between Mimbres Valley utility ware and painted ceramics) become considerably clearer when both chemical and petrographic data are combined.

4. Discussion

Complementary NAA and petrographic analysis of decorated and utility ware from southeastern Arizona and southwestern New Mexico provide critical data on 12th through 14th century ceramic production and exchange in these areas. Overall, the combined results suggest:

1. Similarities in paste recipe among MMS and RRW samples indicate continuity in production locations.
2. RRW vessels from the Mimbres River Valley are chemically and petrographically similar to those from the Upper Gila River Valley.
3. Similar utility and decorated ware paste recipes at some sites along the Upper Gila River and its tributaries and in the Safford Basin suggest local production of both, particularly at 3-Up, Ormand Village, Krider Kiva/Spear Ranch, and possibly Dinwiddie.
4. Based on the current sample, it seems unlikely that TJ Ruin, Dutch Ruin, LA39035, Kuykendall and the Mimbres Valley sites made RRW and MMS pottery.

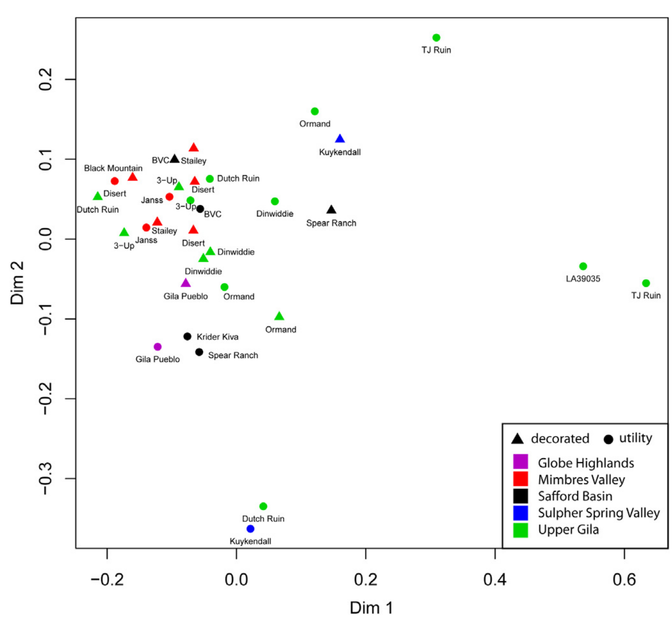

Fig. 7. Multidimensional scaling of combined NAA and petrographic dissimilarity matrices with all samples, including outliers.

In particular, it appears that local production of RRW can be linked to earlier Kayenta settlement at particular villages, a pattern that also has been documented in the San Pedro Valley (Lyons, 2012). Archaeologically, there is evidence for Kayenta groups at three sites, 3-Up, Ormand Village, and Spear Ranch/Krider Kiva, that our data suggest are production locations (see Fig. 1). In contrast, TJ Ruin, Dutch Ruin, and LA 39035 do not appear to have produced decorated ware. Dutch Ruin does have some evidence for Kayenta immigrant groups (Lekson, 2002), but the other two sites do not. Additional sampling may clarify if Dutch Ruin was a producer of decorated pottery. Moreover, differences between the Mimbres Valley utility ware and RRW samples suggest that the latter were imported to the Mimbres Valley, an area that for the most part lacks archaeological indications of Kayenta migrants. These RRW samples appear broadly similar to Upper Gila samples. Additional analysis of sand samples from the Upper Gila River and

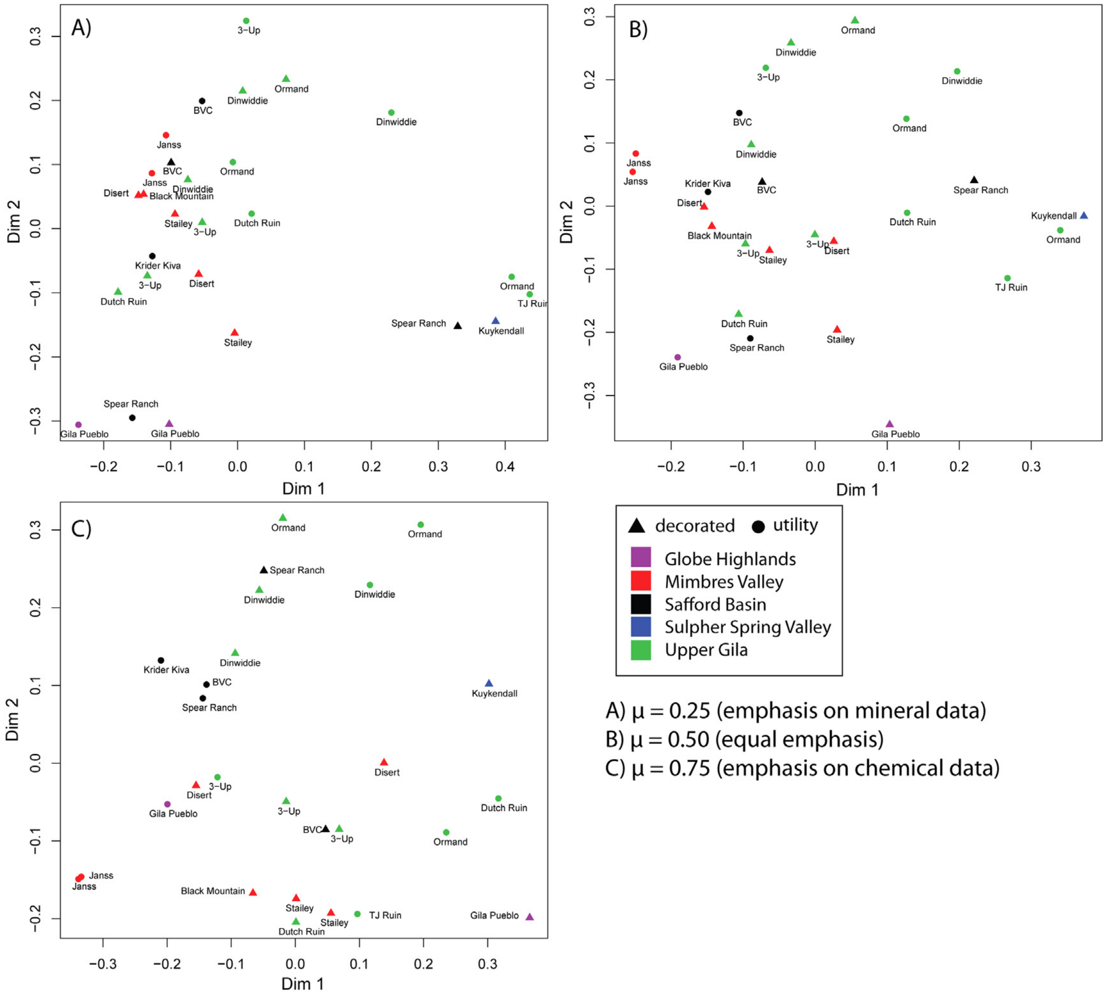

Fig. 8. Multidimensional scaling of combined NAA and petrographic dissimilarity matrices with outliers removed, A) $\mu = 0.25$; B) $\mu = 0.5$; C) $\mu = 0.75$.

its tributaries, which we have planned, is needed to corroborate these patterns.

Production of decorated ware at Kuykendall, BVC, and Gila Pueblo was also not conclusively demonstrated. However, all three sites have archaeological signatures of Kayenta groups suggesting further sampling may reveal local manufacture of decorated ware. This is especially true for Gila Pueblo. The sampled perforated plate from this site has sand temper compatible with local geology, as confirmed by comparison with sand samples collected near the site (Montague-Judd et al., 2003). The fact that none of the decorated samples from Gila Pueblo group chemically with the perforated plate may indicate, particularly for Groups 25 and 27, that potters used different local resources and somewhat different paste recipes to make decorated and utility ware pottery at the site, as they apparently did in the Upper Gila River Valley. Additional sampling is warranted to address this question.

This study supports previous claims that exchange of decorated vessels likely played a role in connecting geographically dispersed 13th through 14th century communities in the southern Southwest. Our results indicate most of the sampled sites received non-local decorated pottery, even those believed to be producers (Fig. 9). Initially, ceramic exchange may have served to keep dispersed Kayenta immigrant communities in touch with one another. As Salado ideology developed beginning in the 13th century, exchange more likely reflected a concern with both community-level and regional social and religious integration. Incongruous in this respect are Krider Kiva and Spear Ranch. Residents of these adjacent villages apparently did not acquire much, if any, non-local decorated pottery, nor did they distribute their products to other villages to the east.

5. Conclusions

We hope that this study will serve as an example of how researchers might use NAA and petrography as complementary techniques. By combining our datasets, we were able to better understand ceramic production and exchange in an area with less than ideal geological diversity. NAA allowed us to identify chemical groups and petrography allowed us to easily relate some chemical groups to a particular provenance. Other groups were more difficult to interpret. This was mostly the result of the widespread OGG outcrop that in some cases frustrated exact identification of producing sites. Further, it is likely that some sites manufacturing decorated ware were not sampled for this study, and some of our chemically diverse groups may contain samples from these sites.

Future studies combining bulk chemical and petrographic datasets may assist in overcoming the shortcomings of each individual method. A major advantage of the mixed-mode approach is that it allows researchers to examine co-associations among samples using various values for μ, which makes it possible to assess the relative contributions of each type of data to apparent patterns. In our case, we were able to highlight the differences between

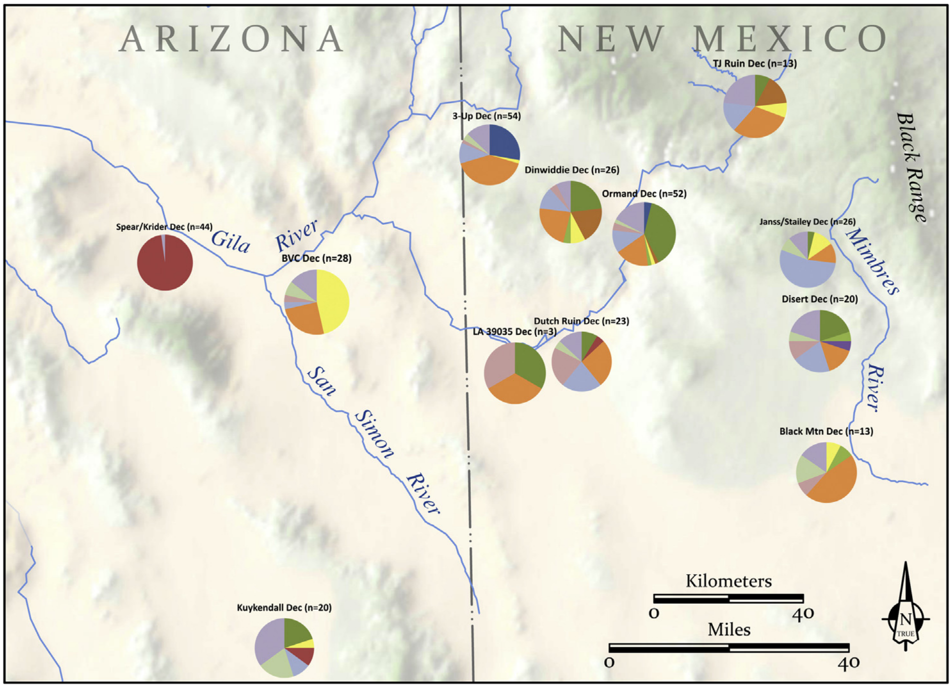

Fig. 9. Map with pie charts showing the consumption of pottery from NAA groups.

Mimbres Valley utility and decorated ware samples that had not been obvious to us based on analysis of the NAA and petrographic datasets alone.

One if the most significant results of this study is that we are able to demonstrate that many villages that made MMS pottery in the 13th century also produced RRW during the 14th century, when the Salado tradition spread throughout the southern Southwest. This information, which supplements previous studies, reinforces current interpretations that Salado identity represented an ideological movement that united migrant and local communities in many areas. However, as our research reveals, there does not appear to be continuity in MMS and RRW production in the Mimbres Valley, a finding that has implications for understanding regional variability in long-distance migration and the spread of Salado identity. The interplay between the results of the two methods increased our confidence in such important archaeological interpretations.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2014.08.018.

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